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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/775,106	02/01/2001	Gerard A. Mourou	UMJ-939-R	4544

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EXAMINER	
EVANS, GEOFFREY S	
ART UNIT	PAPER NUMBER
1725	21

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Please find below and/or attached an Office communication concerning this application or proceeding.

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APPLICATION NO./ CONTROL NO.	FILING DATE	FIRST NAMED INVENTOR / PATENT IN REEXAMINATION	ATTORNEY DOCKET NO.

EXAMINER

ART UNIT	PAPER
	21

DATE MAILED:

Please find below and/or attached an Office communication concerning this application or proceeding.

Commissioner for Patents

See attached letter.

Geoffrey S Evans
Primary Examiner
Art Unit: 1725

PTO-90C (Rev.04-03)

1. A protest against issuance of a patent based upon this application has been filed under 37 CFR 1.291(a) on June 29,2003, and a copy has been served on Applicant. Any comments or reply applicant desires to file before consideration of the protest must be filed by ONE MONTH OR THIRTY DAYS, whichever is longer, of the mailing date of this letter.

Any inquiry concerning this communication or earlier communications from the examiner should be directed to Geoffrey S Evans whose telephone number is (703)-308-1653. The examiner can normally be reached on Mon-Fri 6:30AM to 4:00 PM, alternate Fridays off.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Tom Dunn can be reached on (703)-308-3318. The fax phone numbers for the organization where this application or proceeding is assigned are (703)-872-9310 for regular communications and (703)-872-9311 for After Final communications.

Any inquiry of a general nature or relating to the status of this application or proceeding should be directed to the receptionist whose telephone number is (703)-308-0661.

Geoffrey S Evans
Geoffrey S Evans
Primary Examiner
Art Unit 1725

GSE
July 9, 2003

#20 6/25/03

description requirement of 35 USC 112, as articulated by the CAFC in *Gentry Gallery v. Berline Corp.* 45 USPQ2d 1498.

HISTORY OF REFERENCED REISSUE APPLICATION

The protested reissue application, Appl. Ser. No. 09/775,106 is a divisional application of reissue Appl. Ser. No. 366,685, filed Aug. 4, 1999 and issued on March 19 as US RE37585, which is a reissue of US patent 5,656,186 filed on Apr. 8, 1994 and issued on Aug. 12, 1997. Copending reissue App. Ser. No. 09/ 775,069 filed Feb. 1, 2001 is also a divisional application of reissue Appl. Ser. No. 366,685.

PROTEST UNDER 37 CFR 1.291

MPEP 1441.01 entitled "Protest in Reissue Applications" states:

> A protest with regard to a reissue application should be filed within the 2-month period following the announcement of the filing of the reissue application in the Official Gazette. .... Where the protest is submitted after the 2-month period, **no petition for entry of the protest under 37 CFR 1.182** is needed with respect to the protest being submitted after the 2 months **unless a final rejection has been issued or prosecution on the merits has been closed for the reissue application.** (Emphasis added)

The Office Action of the protested reissue application (US Appl. Ser. No. 09/775,106) mailed April 24, 2003 is not a final rejection and prosecution has not been closed on the merits. Thus, according to MPEP 1441.01 entitled "Protest in Reissue Applications," a petition under 37 CFR 1.182 is not required. The Office Action of the protested reissue application (US Appl. Ser. No. 09/775,106) mailed April 24, 2003 rejects claims 67 and 74-77 as being based upon a defective reissue declaration under 35 USC 251, but, however, indicates at page 10 in paragraph 22 that "[c]laims 67 and 74-77 patentably define over the art of record but are rejected under 35 U.S.C. 251 as stated above." Page 2, paragraph 4 of the office action states "[c]laims 46-80 are rejected as being based upon a defective reissue declaration under 35 U.S.C. 251. ... Receipt of an appropriate supplemental oath/declaration under 37 CFR 1.175(b)(1) will overcome this rejection under 35 USC 251." Thus since there are no other rejections of claims 67 and 74-77, these claims have an implied indication of allowability and in view of this Protestor believe that this Protest is proper.

MPEP 1901.04 permits a protest to be filed after the 2-month period without a petition under 37 CFR 1.182 under the proper circumstances. Protestor is not requesting an extension of the 2-month period, unless it is deemed necessary to enter this Protest at the time of its submission, and thus no petition under 37 CFR 1.182 is required for this purpose except if the USPTO deems an extension of time is required to enter this Protest. If a Petition under 37 CFR 1.182 is required than this paper should be considered a petition under 37 CFR 1.182 and a protest under 37 CFR

1.192. Please charge any fee necessary for such a petition and to enter this paper to deposit account 08/2240.

Protestor is submitting this Protest at this time since they have only recently become aware that the Examiner has indicated that claims 67 and 74-77 are allowable (as indicated above) in the protested reissue application. For the reasons given below, Protestor believes that claims 67 and 74-77 are not supported by the original disclosure of the parent patent, US 5,656,186, of the protested reissue application, as required by the written description requirement of 35 USC 112, first paragraph, and by 35 USC 251.

Since MPEP Section 1901.02 entitled "Information Which Can Be Relied on in Protest" states that "[a]ny information which, in the protestor's opinion, would make the grant of a patent improper can be relied on in a protest under 37 CFR 1.291(a), " protesting the indication of the allowability of claims 67 and 74-77 of the protested reissue application, based on a failure to satisfy the written description requirement of 35 USC 112, first paragraph and the prohibition against the introduction of new matter into a reissue application under 35 USC 251, is proper.

Protestor protests all claims, in particular the indication of allowability of claims, in particular claims 67 and 74-77, in the protested referenced reissue application for failure to satisfy the 35 USC 112, first paragraph, written description requirement. The referenced protested reissue application is a broadening reissue application that has presented for examination claims of broader scope than in the parent patent.

37 CFR 1.173 entitled " Reissue specification, drawings, and amendments." states at 37 CFR 1.173(a) that "**No new matter shall be introduced into the application**." (Emphasis added) and at 37 CFR 1.173 (c) entitled "Status of claims and support for claim changes" states:

> **Whenever there is an amendment to the claims** pursuant to paragraph (b) of this section, **there must also be supplied**, on pages separate from the pages containing the changes, the status (i.e., pending or canceled), as of the date of the amendment, of all patent claims and of all added claims, and **an explanation of the support in the disclosure of the patent for the changes made to the claims.** (Emphasis added)

Thus 37 CFR 1.173(a) requires that "no new matter be introduced in to the [reissue] application" and 37 CFR 1.173 (c) requires that "[w]henever there is an amendment to the claims ... there must also be supplied ... an explanation of the support in the disclosure of the patent for the changes made to the claims." The protested reissue application is a broadening reissue of US 5,656,186 and the protested reissue applicant broadened the scope as compared to the scope of the claims of the parent patent. However, in that part of the protested reissue prosecution papers that the protestor has obtained the reissue applicant did not supply "an explanation of the support in the disclosure of the patent for the changes made to the claims" as required by 37 CFR 1.173 (c) and the examiner did not require the reissue applicant to specifically identify support for the amended or added claims in the specification as required by 37 CFR 1.173 (c).

Claim 1 of US 5656186 is representative of the claims of the parent patent:

> 1. A method for laser induced breakdown (LIB) of a material with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a rapid and distinct change in slope at a characteristic laser pulse width, said method comprising the steps of:
>
> > a. generating a **beam of one or more laser pulses** in which each pulse has a pulse width equal to or less than said characteristic laser pulse width; and
> >
> > **b. focusing said beam to a point at or beneath the surface of the material.** (Emphasis added)

Each of the claims of the parent patent (and each of the original claims filed therein) requires the language, or the equivalent thereof, "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material.**" This language has been broadened, based on the reissued applicant's amendment to the issued claims submitted with the protested reissue application, which were further amended in the response in the protested reissue application received by the USPTO on Nov. 20, 2002. Protested claims 46-50 "directing said beam to the material." There is no support in the parent patent for the language "directing said beam to the material." These claims and claims dependent there from, except claims 67 and 74-77, have been rejected over various prior art references under 35 USC 102 and 103. Multiple dependent claims 67 depends form independent claims 46-50. Dependent claims 74-77 depend from claims 67.

Each of independent claims 46- 50 recites:

> "directing said beam to said material."

Dependent claim 67 states:

> 67. The method according to any of claims 46-50 comprising scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh range.

Thus there is no recitation in each mutiply dependent combination claim 67 of "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material,**" which is required in each of the claims of the parent patent and in each of the original claims filed with the application for the parent patent.

There is no written description support for claim 67 since none of the claims 46-50 recite the language "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material.**" The language recited in independent claims 46-50 "directing said beam to the material" has no support in the protested reissue application or in its

parent patent US 5,656,186. Appendix A is a color coded copy of the text of the parent patent US 5,656,186. A soft copy of the text of this patent was obtained from the USPTO web site, which provides the text of all issued US patents. The word or word which contains the listed word are changed to the color indicated and to small capital letters. This permits a review of the protested reissue application specification to readily determine that there is no written description support for "directing said beam to the material" recited in dependent claim 67 and to clearly show that the language "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material**" is an essential element of the invention of the parent patent of the protested reissue application. The parent patent of the protested reissue application states at Col. 11, lines 46-49.

> While this invention has been described in terms of certain embodiment
> thereof, it is not intended that it be limited to the above description,
> but rather only to the extent set forth in the following claims.

In this paragraph the reissue applicants when they filed the original application states that their inventions is "limited .... to the extent set forth in the following claims, " each of which recited "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material,**" or the equivalent thereof, which is thus an essential element of the claims. The reissue applicant is now eliminating this essential element and merely reciting in claim 67 "directing said beam to said material.... scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh range." The language "scanning the beam along a predetermined path beneath the surface" doses not appear in the parent patent or in the originally filed claims. The closet language to this in the is the language

> scanning said beam along a predetermined path in a longitudinal direction in the
> material to a depth smaller than the Rayleigh range.

which appears in dependent claims 26, 38 and 39 which depends from independent claim 24, 37 and 37, respectively, of the parent patent. (Although Claim 38 does not recite the term "Rayleigh range," it is included since the combination of claims 37/38 read similar to the others listed.) Claim, 26 which depends form claim 24, reads as follows:

> 24. A method for laser induced breakdown of a material which comprises:
>
> ...
>
> **b. focusing said one or more pulses of said beam to a point at or beneath the surface of the material.**
>
> 26. The method according to claim 24 and further including:
>
> .....
>
> c. scanning said beam along a predetermined path in a longitudinal direction in the material to a depth smaller than the <u>Rayleigh range</u>."

Since the protested reissue application is a broadening reissue the changing of the claim language **"focusing said one or more pulses of said beam to a point at or beneath the surface of the material ...** scanning said beam along a predetermined path in a longitudinal direction in the material to a depth smaller than the Rayleigh range" in claims 26, 38 and 39 of the parent patent to read more broadly as "directing said beam to said material.... scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh range," in which there is no recitation of **"focusing ... said beam to a point at or beneath the surface,"** would permit the broadened language of the reissue claim 67 to include an unfocused beam, a collimated beam or where the focus is above the surface for which there is no teaching in the parent patent.

Moreover, there is no support for this language in the originally filed claims of the parent patent. The only support in the parent patent is for the language "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material**." That the language "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material**" of the parent patent is a species of the language "directing said beam to said material" in each of the independent claims 46-50 and "scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh rang" the language of dependent claim 67 of the reissue claims, does not mean that the protested reissue application (and the parent patent) has written description support for this language "directing said beam to said material" in each of the independent claims 46-50 and "scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh range" the language of dependent claim 67 for which there is an indication of allowability.

The language of the protested claims of the protested reissue application is dominant to focusing the beam at any point "at", "beneath" or "above" the surface, or for "not focusing at all." It is clear from a reading of the parent patent that the only concept that the inventors thereof were in possession of at the time of filing of the parent patent was "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material**." Each of the claims of the protested reissue application should recite these words since that is the only recitation that the written description supports. To allow a claim in the protested reissue application that recites "directing said beam to said material" in each of the independent claims 46-50 and "scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh range" of dependent claim 67 permits the reissue applicant to claim an invention that they did not disclose in there application. The missing teaching cannot be provided by affidavit, even if the inventor can show that they did conceive of "directing said beam to said material" and "scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh range" prior to filing of the parent patent application since there is no evidence from the written description of the parent patent application that they were in possession of anything more than "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material**." Even if a person of skill in the art from the teaching of the parent patent could be enabled to

"directing said beam to said material" and "scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh range," the reissue applicant is not entitled to claim this when their written description fails to support this claim language without the missing essential element. The parent patent clearly shows that the reissue applicant did not invent what they are now claiming.

Table of Selected Words in the Parent Patent
and
Color Coding for These Words as Displayed in That Color and in Small Capital Letters in the Copy of the Text of the Parent Patent In Appendix A

Word	Color	Appearance in Appendix A	Number of Occurrences
laser	red	LASER	173
pulse	dark blue	PULSE	240
direct	light green	DIRECT	9
at or below	light blue	AT OR BELOW	2
at or beneath	light blue	AT OR BENEATH	13
path	brown	PATH.	12
focus	dark green	FOCUS	28
beam	dark pink	BEAM	103
surface	purple	SURFACE	17
Rayleigh	olive green	RAYLEIGH	12

The 12 occurrences of the word Rayleigh are never used in the teaching other than in combination with the "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material,** " or the equivalent thereof. The 12 occurrences are:

Abstract

"The beam is focused to a point at or beneath the surface of a material where laser induced breakdown is desired. ... The technique can produce features smaller than the spot size and Rayleigh range due to enhanced damage threshold accuracy in the short pulse regime."

Claim 24/ 26:

24. A method for laser induced breakdown of a material which comprises:

...

b. focusing said one or more pulses of said beam to a point at or beneath the surface of the material.

26. The method according to claim 24 and further including:

.....

.....

c. scanning said beam along a predetermined path in a longitudinal direction in the material to a depth smaller than the Rayleigh range."

Claim: 37/38

37. A method for laser induced breakdown of a material which comprises:

...

d. focusing said one or more pulses of said beam to a point at or beneath the surface of the material.

38. The method according to claim 37 and further including:

...

b. **focusing the laser beam initial start point at or beneath the surface of the material**; and

c. scanning said beam along a predetermined path in a transverse direction.

(Note, although as stated above Rayleigh range is not recited in Claim 37/38 it is listed here since the language is similar to the other claims.)

Claim 37,39:

37. A method for laser induced breakdown of a material which comprises:

...

d. **focusing said one or more pulses of said beam to a point at or beneath the surface of the material.**

39. The method according to claim 37 and further including:

a. identifying a pulse width start point;

b. focusing the laser beam initial start point at or beneath the surface of the material; and

c. scanning said beam along a predetermined path in a longitudinal direction in the material to a depth smaller than the Rayleigh range.

Col. 2, lines 44-62:

"In one aspect, the method of the invention provides a laser beam which defines a spot that has a lateral gaussian profile characterized in that fluence at or near the center of the beam spot is greater than the threshold fluence whereby the laser induced breakdown is ablation of an area within the spot. The maximum intensity is at the very center of the beam waist. The beam waist is the point in the beam where wave-front becomes a perfect plane; that is, its radius of curvature is infinite. This center is at radius R=0 in the x-y axis and along the Z axis, Z=0. This makes it possible to damage material in a very small volume Z=0, R=0. Thus it is possible to make features smaller than spot size in the x-y focal plane and smaller than the <u>Rayleigh</u> <u>range</u> (depth of focus) in the Z axis. It is preferred that the pulse width duration be in the femtosecond range
although pulse duration of higher value may be used so long as the value is less than the pulse width defined by an abrupt or discernible change in slope of fluence breakdown threshold versus laser beam pulse width."

Col. 6, lines 47-49:
"Those skilled in the art will understand that the basic method of the invention may be utilized in alternative embodiments depending on the desired configurations of the induced breakdown. Examples include, but are not limited to using a mask in the beam path, varying spot size, adjusting focus position by moving the lens, adjusting laser cavity design, Fourier Transform (FT) shaping, using a laser operating mode other than TEMoo, and adjusting the <u>Rayleigh range</u>, the depth of focus or beam waist."

Col. 6, lines 66-67:
"The <u>Rayleigh range</u> (Z axis) may be adjusted by varying the beam diameter, where the <u>focal plane</u> is in the x-y axis."

Col. 7, lines 11-12:
"The <u>Rayleigh length</u> of the focused beam is .about. 2 mm."

Col. 8, lines 2-6:
"It is possible **to make features** smaller than spot size **in the x-y focal plane** and smaller than the <u>Rayleigh range</u> (depth of focus) in the longitudinal direction or Z axis. **These elements are essential to making features smaller than spot size or <u>Rayleigh range</u>**."

Col. 10, lines 51-60:
"The beam intensity as a function of R and Z expressed as
{equation}
where Z.sub.R is the <u>Rayleigh range</u> and is equal to
{equation}
W.sub.o is the beam size at the waist (Z=0)."

We can see that the highest value of the field is at Z=R=0 at the center of the waist. If the threshold is precisely defined it is possible **to damage the material precisely at the waist** and have a damaged volume representing only a fraction of the waist in the R direction or in the Z direction. It is very important to control precisely the damage threshold or the laser intensity fluctuation."

Col. 11, lines 1-7:
For example, if the damage threshold or the laser fluctuations known within 10% that means that on the axis (R=0)
{equation}
damaged volume can be produced at a distance Z.sub.R /3 where Z.sub.R again is the Rayleigh range.

Col. 11, lines 19-27:
The maximum intensity is exactly at the center of the beam waist (Z=0, R=0). For a sharp threshold **it is possible to damage transparent, dielectric material in a small volume centered around the origin point (Z=0, R=0).** The damage would be much smaller than the beam waist in the R direction. Small cavities, holes, or damage can have dimensions smaller than the Rayleigh range (Z.sub.R) in the volume of the transparent, dielectric material.

The passages quoted above from the abstract, Claim 24/26, Claim 37/38, and Claim 37/39; refer to the Rayleigh range and each states "The beam is focused to a point at or beneath the surface of a material where laser induced breakdown is desired,." or the equivalent thereof. (Note, although as stated above Rayleigh range is not recited in Claim 37/38 it is listed here since the language is similar to the other claims.)

Although the reference to the Rayleigh range in the passage from Col. 2, lines 44-46 does not refer to the word "focus" of the beam, it teaches "This center is at radius R=0 in the x-y axis and along the Z axis, Z=0. This makes it possible to damage material in a very small volume Z=0, R=0. Thus it is possible to make features smaller than spot size in the x-y focal plane and smaller than the Rayleigh range (depth of focus) in the Z axis." The location R=0, Z=0 is the focus of the beam. By stating that "This makes it possible to damage material in a very small volume Z=0, R=0" the reissue applicant teaches that damage occurs at the focus of the beam, that is the focus of the beam is "at or beneath" the surface. Otherwise that would be no damage at the location Z=0, R=0 of the beam which is the focal point.

The passage quoted from Col. 6, lines 47-49 teaches "adjusting the Rayleigh range." That this passage does not refer to the location of the focus of the beam does not mean that this passage can be read to mean that the beam does not have a focus or that the focus can be locate in a location other that "at or below the surface" as taught throughout the parent patent, for example in the passage quoted for Col. 2.

The passage quoted from Col. 6 line 66-67, teaches that the Rayleigh range may be adjusted by varying the beam diameter, which is W_0 of the equation at Col. 10 line 57. That this passage does not refer to the location of the focus of the beam does not mean that this passage can be read to mean that the beam does not have a focus or that the focus can be locate in a location other that "at or below the surface" as taught throughout the parent patent. This passage also teaches the x-y axis referred to in the parent patent is the focal plane of the beam.

The passage quoted from Col. 7, lines 11-12 gives an example of Rayleigh length. That this passage does not refer to the location of the focus of the beam does not mean that this passage can be read to mean that the beam does not have a focus or that the focus can be locate in a location other that "at or below the surface" as taught throughout the parent patent.

The passage quoted from Col. 8, lines 2-6, teaches "to make features… in the x-y focal plane." This clearly means that the focus of the beam is "at or below the surface" since a feature is made by laser induced breakdown. Thus if a feature is made at the x-y focal plane, the focal plane **must be at or below the surface.** The passage further states **"These elements are essential to making features." Thus that the x-y focal plane be "at or beneath the surface" is essential to the invention.** That this passage does not refer to the location of the focus of the beam does not mean that this passage can be read to mean that the beam does not have a focus or that the focus can be locate in a location other that "at or below the surface" as taught throughout the parent patent and as explicitly taught by other language in this passage.

The passage quoted from Col. 10, lines 51-60, teaches an equation for the Rayleigh range. That this passage does not refer to the location of the focus of the beam does not mean that this passage can be read to mean that the beam does not have a focus or that the focus can be locate in a location other that "at or below the surface" as taught throughout the parent patent. This passage teaches "to damage the material precisely at the waist," an that "Z=R=0 [is] at the center of the waist." The location Z=R=0 is the focal point. If the material is damaged at the waist, then the waist **must be** **"at or below the surface."**

The passage quoted from Col. 11, lines 1-7 immediately follows the passage from Col. 10, lines 51-60, which as show above teaches that the focus is at or below the surface. The passage form Col. 11, lines 1-7, further teaches "damage volume can be produce at a distance $Z_R/3$ where Z_R is the Rayleigh range." Thus there is damage beneath the surface of the material to a depth smaller than the Rayleigh range, but the focus is required to be at or beneath the surface.

The passage quoted from Col. 11, lines 19-27, teaches "damage can have dimensions smaller than the Rayleigh range, " and also teaches that "it is possible to damage … material in a small volume centered around the origin point (Z=0, R=0)" This origin point is the focal point. If damage is centered around the focal point, then the focus **must be "at or beneath the surface."**

Thus the recitation in the protested reissue claims 67 and 74-77 is missing the essential element "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material.**" That the language "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material.**"

The 9 occurrences of the word "direct" or words containing the word "direct" are not used for "directed towards the surface" as in the reissue claims. In fact, the word "directed" recited in the reissue claims does not appear in the text of the parent patent. The letter sequence "direct" only appears in the text of the parent patent as part of the word "direction." The 9 occurrences of "direct", underlined in the quoted passages" are:

> Abstract "The beam may be used in combination with a mask in the beam path. The beam or mask may be moved in the x, y, and Z <u>direct</u>ions to produce desired features."
>
> Claim 25: "c. scanning said beam along a predetermined path in a transverse <u>direct</u>ion"
>
> Claim 26: "c. scanning said beam along a predetermined path in a longitudinal <u>direct</u>ion in the material to a depth smaller than the Rayleigh range"
>
> Claim 38: "c. scanning said beam along a predetermined path in a transverse direction."
>
> Claim 39 "c. scanning said beam along a predetermined path in a longitudinal direction in the material to a depth smaller than the Rayleigh range."
>
> Col. 8, lines 2-5: "It is possible to make features smaller than spot size in the x-y focal plane and smaller than the Rayleigh range (depth of focus) in the longitudinal direction or Z axis."
>
> Col. 10, lines 59-67: If the threshold is precisely defined it is possible to damage the material precisely at the waist and have a damaged volume representing only a fraction of the waist in the R direction or in the Z <u>direct</u>ion. It is very important to control precisely the damage threshold or the laser intensity fluctuation.
>
> Col. 11, lines 23-25: "The damage would be much smaller than the beam waist in the R <u>direct</u>ion."

It is clear from these passages that there is no support for the language "directing said beam to said material." and "scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh range" of the protested reissue application without the missing essential element "**beam of** one or more

laser **pulses … and focusing said beam to a point at or beneath the surface of the material**."

The 17 occurrences of the word "surface," underlined in the quoted passages below, are listed here:

> Abstract "The beam is focused to a point at or beneath the surface of a material where laser induced breakdown is desired."
>
> References: ": "C.V. Shank, R. Yen, and C. Hirlimann, "Femtosecnd-Time-Resolved Surface Structural Dynamics of Optically Excited Silicon",
>
> Claim 1: "b. focusing said beam to a point at or beneath the surface of the material"
>
> Claim 7: "b. focusing said beam to a point at or beneath the surface of the material."
>
> Claim 24: "b. focusing said one or more pulses of said beam to a point at or beneath the surface of the material."
>
> Claim 25 "b. focussing the laser beam initial start point at or beneath the surface of the material;"
>
> Claim 26 "b. focussing the laser beam initial start point at or beneath the surface of the material;"
>
> Claim 33 "b. focusing said beam to a point at or beneath the surface of the material"
>
> Claim 35 "b. focusing said beam to a point at or beneath the surface of the material"
>
> Claim 36 "b. focusing said beam to a point at or beneath the surface of the material and inducing breakdown by plasma formation in the material."
>
> Claim 37 "d. focusing said one or more pulses of said beam to a point at or beneath the surface of the material"
>
> Claim 38 "b. focusing the laser beam initial start point at or beneath the surface of the material;"
>
> Claim 39 "b. focusing the laser beam initial start point at or beneath the surface of the material"

Filed of the Invention "This invention relates generally to methods utilizing lasers for modifying internal and external surfaces of material such as by ablation or changing properties in structure of materials. This invention may be used for a variety of materials."

Summary of The Invention: "The beam is focused to a point at or beneath the surface of a material where laser induced breakdown is desired."

Col. 8, lines 37-39: "In summary, it has been demonstrated that sub-wavelength holes can be machined into metal surfaces using femtosecond laser pulses."

Col. 10, lines 11-14 "This factor of 1.7 is of relatively minor importance, as it can be due to a systematic correction, or because breakdown occurred on the surface first, which could have a lower threshold."

Each of the above 17 quoted passages from the parent patent of the protested reissue application require focusing said one or more pulses of a laser beam to a point at or beneath the surface of the material, except for the passages quoted from the Field of the Invention, from Col. 8 and from Col. 10. Since the field of the invention only describes the general subject that the invention is directed to, it cannot broaden the scope of the invention as it is otherwise limited and described. The passage quoted from Col. 8 summarizes the result of the disclosed process "holes can be machined into metal surfaces using femtosecond laser pulses." The passage quoted from Col. 10 does not describe how the laser beam or pulses are directed to the surface. Thus the passages from Col. 8 and Col. 10 cannot broaden the scope of the invention as it is otherwise limited and described.

Fig. 5 shows the focal plane at the ablated area, that is, the focus of the beam is at the surface.

Fig. 13 B shows the focus below the surface.

Example 1 described at Col. 1 and 6 refers to Fig. 1 at Col. 5, line 13. Fig. 1 shows a lens focusing the laser beam on the sample target surface. In regard to examples 1 US 5,656,186 states at Col. 6, lines 41-49:

> Those skilled in the art will understand that the basic method of the invention may be utilized in alternative embodiments depending on the desired configurations of the induced breakdown. Examples include, but are not limited to using a mask in the beam path, varying spot size, adjusting focus position by moving the lens, adjusting laser cavity design, Fourier Transform (FT) shaping, using a laser operating mode other than TEMoo, and adjusting the Rayleigh range, the depth of focus or beam waist.

Although, this paragraph states " adjusting focus position by moving the lens" there is no teaching that the "adjusting focus positions" should not be limited to "focusing said beam to a

point at or beneath the surface of the material" as stated so many times in the specification and as indicated in Fig. 1, as referred to in the description of Example 1 and in many other locations of the parent patent.

The description of Example 2 described at Col. 7-8 states at Col. 7, lines 9-10 "[t]he laser pulse was focused by an f=25 cm lens inside the SiO_2 sample." (Emphasis added.) Thus Example 2 clearly states that the laser pulse was focused inside the sample.

The description of Example 3 described at Col. 8-9 sates Col. 8 lines 16-17 "[t]he laser was focused to a spot size (FWHM) of 26 .mu.m in diameter." Although, this does not explicitly state were the focus is located there is no teaching that the focus position should be not be limited to "focusing said beam to a point at or beneath the surface of the material" as stated so many times in the specification and as indicated in the figures.

The 28 occurrences of the word "focus", underlined in the quoted passages below, are listed here:

> Abstract: "The beam is focused to a point at or beneath the surface of a material where laser induced breakdown is desired."
>
> References; "J. Squier and G. Mourou, "Tunable Solid-State Lasers Create Ultrashort Pulses", Laser Focus World, (Jun. 1992).
>
> Claim 1: "b. focusing said beam to a point at or beneath the surface of the material."
>
> Claim 7: "b. focusing said beam to a point at or beneath the surface of the material."
>
> Claim 24: "b. focusing said one or more pulses of said beam to a point at or beneath
> the surface of the material."
>
> Claim 25: "b. focussing the laser beam initial start point at or beneath the surface of the material; and"
>
> Claim 26: "b. focussing the laser beam initial start point at or beneath the surface of the material;"
>
> Claim 33: "b. focusing said beam to a point at or beneath the surface of the material
> so that the laser beam defines a spot and has a lateral gaussian profile characterized in that fluence at or near the center of the beam spot is greater than the threshold fluence whereby the laser induced breakdown is ablation of an area within the spot."

Claim 35: "b. <u>focus</u>ing said beam to a point at or beneath the surface of the material
which is biological tissue, the pulse width is 10 to 10,000 femtoseconds and the beam has an energy of 10 nanojoules to 1 millijoule."

Claim 36: "b. <u>focus</u>ing said beam to a point at or beneath the surface of the material
and inducing breakdown by plasma formation in the material."

Claim 37: "d. <u>focus</u>ing said one or more pulses of said beam to a point at or beneath
the surface of the material"

Claim 38: "b. <u>focus</u>ing the laser beam initial start point at or beneath the surface of
the material;"

Claim 39: "b. <u>focus</u>ing the laser beam initial start point at or beneath the surface of
the material;"

Col. 1, lines 33-37: "Although the laser beam is <u>focus</u>ed onto an area having a selected diameter, the effect of the beam extends beyond the <u>focus</u>ed area or spot to adversely affect peripheral areas adjacent to the spot."

Summary of the Invention Col. 1 lines 59-61 "The beam is <u>focus</u>ed to a point at or beneath the surface of a material where laser induced breakdown is desired."

Col. 4, lines 23-26: Chirped-pulse amplification systems have been described by Jeffrey Squier
and Gerard Mourou, two of the joint inventors in the present application, in a publication entitled Laser <u>Focus</u> World published by Pennwell in June of 1992.

Col. 6, lines 13-15: "The beam was <u>focus</u>ed with a 10 times. objective, implying a theoretical spot size of 3.0 .mum in diameter."

Col. 6, lines 45-49: "Examples include, but are not limited to using a mask in the beam path, varying spot size, adjusting <u>focus</u> position by moving the lens, adjusting laser cavity design, Fouler Transform (FT) shaping, using a laser operating mode other than Tempo, and
adjusting the Rayleigh range, the depth of <u>focus</u> or beam waist. "

Col. 7, lines 9-13: "The laser pulse was <u>focus</u>ed by an f=25 cm lens inside the SiO.sub.2 sample. The Rayleigh length of the <u>focus</u>ed beam is .about.2 mm. The <u>focus</u>ed spot size was measured in-situ by a microscope objective lens."

Col. 7, lines 18-19: "Thin samples were used in order to avoid the complications of self-focusing of the laser pulses in the bulk."

Col. 7, lines 35-38: "Due to the spatial variation of the intensity, the breakdown will reach
threshold at the center of the focus, and because of the short pulse duration, the generated plasma will stay localized."

Col. 8, lines 2-5 "Thus it is possible to make features smaller than spot size in the x-y focal
plane and smaller than the Rayleigh range (depth of focus) in the Z axis."

Col. 8, lines 16-17: "The laser was focused to a spot size (FWHM) of 26 .mu.m in diameter."

The above quoted passages from the parent patent of the protested reissue application require **focusing said one or more pulses of a laser beam to a point at or beneath the surface of the material**. None of these passages support the language "directing said beam to said material." and "scanning the beam along a predetermined path beneath the surface of the material to induce laser induced breakdown therein to a depth smaller than the Rayleigh range" recited in the claims of the protested reissue application without reciting the missing essential element "**beam of** one or more laser **pulses ... and focusing said beam to a point at or beneath the surface of the material.**"

The objected to new matter was introduced into the claims of the protested reissue application as the added claims 58-92 filed with the reissue application, which were renumbered as claims 46-80 and simultaneously modified in the amendment dated April 3, 2002. The changes in independent claims 46-50 are not in compliance with 37 CFR 1.173. This has obfuscated the broadening in language or the claims (in particular claims 46-50 and 67 and 74-77) to include language that is not supported by the specification of the parent patent, which is therefore, new matter the introduction of which is prohibited by 35 USC 112 and 251. .

37 CFR 1.173(b) entitled "Making amendments in a reissue application" states:

> An amendment in a reissue application is made either by physically incorporating the changes into the specification when the application is filed, or by a separate amendment paper. **If amendment is made by incorporation, markings pursuant to paragraph (d) of this section must be used.**." (Emphasis added.)

37 CFR 1.73(b)(2)(2) entitled "Claims" states:

> An amendment paper must include the entire text of each claim being changed by such amendment paper and of each claim being added by such amendment paper.

.... **Each changed patent claim** and each added claim <u>**must**</u> **include markings pursuant to paragraph (d) of this section**, . (Emphasis added.)

37 CFR 1.173(d) entitled "Changes shown by markings" states:

> Any changes relative to the patent being reissued which are made to the specification, including the claims, upon filing, or by an amendment paper in the reissue application, must include the following markings:
>
> (1) The **matter to be omitted by reissue must be enclosed in brackets**; and
>
> (2) The **matter to be added by reissue must be underlined,**
>
> (Emphasis added.)

The reissue applicant in amending claims 46-50 between the amendment therein dated April 3, 2002 and the amendment therein dated Nov. 20, 2002 did not comply with 37 CFR 1.173. Table 2 below is a comparison of claim 46 as of the amendment dated April 3, 2002 (column 1); how it was presented in the amendment dated Nov. 20, 2002 , all underlined and not in compliance with 37 CFR 1.173, (column. 2); and how it should have been amended to be in compliance with 37 CFR 1.173 (column 3).

Moreover, added claims 75, 76, and 77, for which there is an indication of allowability, have no support in the parent patent. As to claim 74 there is no teaching of the range 10 femtoseconds to 10 picoseconds. As to claim 75 there is no teaching of a pulse having a energy in the range of 1 pocojule and 1 joule. As to claim 76 there is no teaching of a repetition rate of 100 million pulse per second. As to claim 77 there is no teaching of the recited wavelength ranges.

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Goverment Interests

GOVERNMENT RIGHTS

This invention was made with government support provided by the Office of Naval Research and the National Science Foundation under the terms of No. STC PHY 8920108. The government has certain rights in the invention.

Claims

We claim:

1. A method for LASER induced breakdown (LIB) of a material with a PULSED LASER BEAM, the material being characterized by a relationship of fluence breakdown threshold versus LASER PULSE width that exhibits a rapid and distinct change in slope at a characteristic LASER PULSE width, said method comprising the steps of:

a. generating a BEAM of one or more LASER PULSES in which each PULSE has a PULSE width equal to or less than said characteristic LASER PULSE width; and

b. FOCUSING said BEAM to a point AT OR BENEATH the SURFACE of the material.

2. The method according to claim 1 wherein the material is a metal, the PULSE width is 10 to 10,000 femtoseconds, and the BEAM has an energy of 1 nanojoule to 1 microjoule.

3. The method according to claim 1 wherein the spot size is varied within a range of 1 to 100 microns by changing the f number of the LASER BEAM.

4. The method according to claim 1 wherein the spot size is varied within a range of 1 to 100 microns by varying the target position.

5. The method according to claim 1 wherein the material is transparent to radiation emitted by the LASER and the PULSE width is 10 to 10,000 femtoseconds, the BEAM has an energy of 10 nanojoules to 1 millijoule.

6. The method according to claim 1 wherein the material is biological tissue, the PULSE width is 10 to 10,000 femtoseconds and the BEAM has an energy of 10 nanojoules to 1 millijoule.

7. A method for LASER induced breakdown (LIB) of a material with a PULSED LASER BEAM, the material being characterized by a relationship of fluence breakdown threshold versus LASER PULSE width that exhibits a rapid and distinct change in slope at a predetermined LASER PULSE width where the onset of plasma induced breakdown occurs, said method comprising the steps of:

a. generating a BEAM of one or more LASER PULSES in which each PULSE has a PULSE width equal to or less than said predetermined LASER PULSE width obtained by determining the ablation (LIB) threshold of the material as a function of PULSE width and by determining where the ablation (LIB) threshold function is no longer proportional to the square root of PULSE width; and

b. FOCUSing said BEAM to a point AT OR BENEATH the SURFACE of the material.

8. The method according to claim 1 wherein the LASER BEAM has an energy in a range of 10 nanojoules to 1 millijoule.

9. The method according to claim 1 wherein the LASER BEAM has a fluence in a range of 100 millijoules per square centimeter to 100 joules per square centimeter.

10. The method according to claim 1 wherein the LASER BEAM defines a spot in or on the material and the LIB causes ablation of an area having a size smaller than the area of the spot.

11. The method according to claim 1 wherein the LASER BEAM has a wavelength in a range of 200 nanometers to 2 microns.

12. The method according to claim 1 wherein the PULSE width is in a range of a few picoseconds to femtoseconds.

13. The method according to claim 1 wherein the breakdown includes changes caused by one or more of ionization, free electron multiplication, dielectric breakdown, plasma formation, and vaporization.

14. The method according to claim 1 wherein the breakdown includes plasma formation.

15. The method according to claim 1 wherein the breakdown includes disintegration.

16. The method according to claim 1 wherein the breakdown includes ablation.

17. The method according to claim 1 wherein the breakdown includes vaporization.

18. The method according to claim 1 wherein the spot size is varied by flexible diaphragm to a range of 1 to 100 microns.

19. The method according to claim 1 wherein a mask is placed in the PATH of the BEAM to block a portion of the BEAM to cause the BEAM to assume a desired geometric configuration.

20. The method according to claim 1 wherein the LASER operating mode is non-TEMoo.

21. The method according to claim 1 wherein the LASER BEAM defines a spot and has a lateral gaussian profile characterized in that fluence at or near the center of the BEAM spot it greater than the threshold fluence whereby the LASER induced breakdown is ablation of an area within the spot.

22. The method according claim 22 wherein the spot size is a diffraction limited spot size providing an ablation cavity having a diameter less than the fundamental wavelength size.

23. The method according to claim 1 wherein the characteristic PULSE width is obtained by determining the ablation (LIB) threshold of the material as a function of PULSE width and determining where the ablation (LIB) threshold function is no longer proportional to the square root of PULSE width.

24. A method for LASER induced breakdown of a material which comprises:

a. generating a BEAM of one or more LASER PULSES in which each PULSE has a PULSE width equal to or less than a PULSE width value corresponding to a change in slope of a curve of fluence breakdown threshold (F.sub.th) as a function of LASER PULSE width (T), said change occurring at a point between first and second portions of said curve, said first portion spanning a range of relatively long PULSE width where F.sub.th varies with the square root of PULSE width (T.sup.1/2) and said second portion spanning a range of short PULSE width relative to said first portion with a F.sub.th versus T slope which differs from that of said first portion; and

b. FOCUSING said one or more PULSES of said BEAM to a point AT OR BENEATH the SURFACE of the material.

25. The method according to claim 24 and further including:

a. identifying a PULSE width start point;

b. FOCUSSING the LASER BEAM initial start point AT OR BENEATH the SURFACE of the material; and

c. scanning said BEAM along a predetermined PATH in a transverse DIRECTION.

26. The method according to claim 24 and further including:

a. identifying a PULSE width start point;

b. FOCUSSING the LASER BEAM initial start point AT OR BENEATH the SURFACE of the material; and

c. scanning said BEAM along a predetermined PATH in a longitudinal DIRECTION in the material to a depth smaller than the RAYLEIGH range.

27. The method according to claim 24 wherein the breakdown includes changes caused by one or more of ionization, free electron multiplication, dielectric breakdown, plasma formation, and vaporization.

28. The method according to claim 24 wherein the breakdown includes plasma formation.

29. The method according to claim 24 wherein the breakdown includes disintegration.

30. The method according to claim 24 wherein the breakdown includes ablation.

31. The method according to claim 24 wherein the breakdown includes vaporization.

32. The method according to any one of claims 1, 2, 5 or 24 wherein said BEAM is obtained by chirped-PULSE amplification (CPA) means comprising means for generating a short optical PULSE having a predetermined duration; means for stretching such optical PULSE in time; means for amplifying such time-stretched optical PULSE including solid state amplifying media; and means for recompressing such amplified PULSE to its original duration.

33. A method for LASER induced breakdown (LIB) of a material with a PULSED LASER BEAM, the material being characterized by a relationship of fluence breakdown threshold versus LASER PULSE width that exhibits a rapid and distinct change in slope at a predetermined LASER PULSE width where the onset of plasma induced breakdown occurs, said method comprising the steps of:

a. generating a BEAM of one or more LASER PULSES in which each PULSE has a PULSE width equal to or less than said predetermined LASER PULSE width; and

b. FOCUSING said BEAM to a point AT OR BENEATH the SURFACE of the material so that the LASER BEAM defines a spot and has a lateral gaussian profile characterized in that fluence at or near the center of the BEAM spot is greater than the threshold fluence whereby the LASER induced breakdown is ablation of an area within the spot.

34. The method according to claim 33 wherein the spot size is a diffraction limited spot size providing an ablation cavity having a diameter less than the fundamental wavelength size.

35. A method for LASER induced breakdown (LIB) of a material with a PULSED LASER BEAM, the material being characterized by a relationship of fluence breakdown threshold versus LASER PULSE width that exhibits a rapid and distinct change in slope at a predetermined LASER PULSE width where the onset of plasma induced breakdown occurs, said method comprising the steps of:

a. generating a BEAM of one or more LASER PULSES in which each PULSE has a PULSE width equal to or less than said predetermined LASER PULSE width; and

b. FOCUSING said BEAM to a point AT OR BENEATH the SURFACE of the material which is biological tissue, the PULSE width is 10 to 10,000 femtoseconds and the BEAM has an energy of 10 nanojoules to 1 millijoule.

36. A method for LASER Induced breakdown (LIB) of a material by plasma formation with a PULSED LASER BEAM, the material being characterized by a relationship of fluence breakdown threshold versus LASER PULSE width that exhibits a distinct change in slope at a characteristic LASER PULSE width, said method comprising the steps of:

a. generating a BEAM of one or more LASER PULSES in which each PULSE has a PULSE width equal to or less than said characteristic LASER PULSE width, said characteristic PULSE width being defined by the ablation (LIB) threshold of the material as a function of PULSE width where the ablation (LIB) threshold function is no longer proportional to the square root of PULSE width; and

b. FOCUSING said BEAM to a point AT OR BENEATH the SURFACE of the material and inducing breakdown by plasma formation in the material.

37. A method for LASER induced breakdown of a material which comprises:

a. determining, for a selected material, a characteristic curve of fluence breakdown threshold (F.sub.th) as a function of LASER PULSE width;

b. identifying a PULSE width value on said curve corresponding to a rapid and distinct change in slope of said F.sub.th versus PULSE width curve characteristic of said material;

c. generating a BEAM of one or more LASER PULSES, said having a PULSE width AT OR BELOW said PULSE width value corresponding to said distinct change in slope; and

d. FOCUSING said one or more PULSES of said BEAM to a point AT OR BENEATH the SURFACE of the material.

38. The method according to claim 37 and further including:

a. identifying a PULSE width start point;

b. FOCUSING the LASER BEAM initial start point AT OR BENEATH the SURFACE of the material; and

c. scanning said BEAM along a predetermined PATH in a transverse DIRECTION.

39. The method according to claim 37 and further including:

a. identifying a PULSE width start point;

b. FOCUSing the LASER BEAM initial start point AT OR BENEATH the SURFACE of the material; and

c. scanning said BEAM along a predetermined PATH in a longitudinal DIRECTion in the material to a depth smaller than the RAYLEIGH range.

40. The method according to claim 37 wherein the breakdown includes changes caused by one or more of ionization, free electron multiplication, dielectric breakdown, plasma formation, and vaporization.

41. The method according to claim 37 wherein the breakdown includes plasma formation.

42. The method according to claim 37 wherein the breakdown includes disintegration.

43. The method according to claim 37 wherein the breakdown include ablation.

44. The method according to claim 37 wherein breakdown includes vaporization.

45. The method according to any one of claims 35, or 37 wherein said BEAM is obtained by chirped-PULSE amplification (CPA) means comprising means for generating a short optical PULSE having a predetermined duration; means for stretching such optical PULSE in time; means for amplifying such time-stretched optical PULSE including solid state amplifying media; and means for recompressing such amplified PULSE to its original duration.

Description

FIELD OF THE INVENTION

This invention relates generally to methods utilizing LASERS for modifying internal and external SURFACES of material such as by ablation or changing properties in structure of materials. This invention may be used for a variety of materials.

BACKGROUND OF THE INVENTION

LASER induced breakdown of a material causes chemical and physical changes, chemical and physical breakdown, disintegration, ablation, and vaporization. LASERS provide good control for procedures which require precision such as inscribing a micro pattern. PULSED rather than continuous

BEAMS are more effective for many procedures, including medical procedures. A PULSED LASER BEAM comprises bursts or PULSES of light which are of very short duration, for example, on the order of 10 nanoseconds in duration or less. Typically, these PULSES are separated by periods of quiescence. The peak power of each PULSE is relatively high often on the order of gigawatts and capable of intensity on the order of 10.sup.13 w/cm.sup.2. Although the LASER BEAM is FOCUSED onto an area having a selected diameter, the effect of the BEAM extends beyond the FOCUSED area or spot to adversely affect peripheral areas adjacent to the spot. Sometimes the peripheral area affected is several times greater than the spot itself. This presents a problem, particularly where tissue is affected in a medical procedure. In the field of LASER machining, current LASERS using nanosecond PULSES cannot produce features with a high degree of precision and control, particularly when nonabsorptive wavelengths are used.

It is a general object to provide a method to localize LASER induced breakdown. Another object is to provide a method to induce breakdown in a preselected pattern in a material or on a material.

SUMMARY OF THE INVENTION

In one aspect the invention provides a method for LASER induced breakdown of a material with a PULSED LASER BEAM where the material is characterized by a relationship of fluence breakdown threshold (F.sub.th) versus LASER BEAM PULSE width (T) that exhibits an abrupt, rapid, and distinct change or at least a clearly detectable and distinct change in slope at a predetermined LASER PULSE width value. The method comprises generating a BEAM of LASER PULSES in which each PULSE has a PULSE width equal to or less than the predetermined LASER PULSE width value. The BEAM is FOCUSED to a point AT OR BENEATH the SURFACE of a material where LASER induced breakdown is desired.

In one aspect, the invention may be understood by further defining the predetermined LASER PULSE width as follows: the relationship between fluence breakdown threshold and LASER PULSE defines a curve having a first portion spanning a range of relatively long (high) PULSE width where fluence breakdown threshold (F.sub.th) varies with the square root of PULSE width (T.sup.1/2). The curve has a second portion spanning a range of short (low) PULSE width relative to the first portion. The proportionality between fluence breakdown threshold and PULSE width differ in the first and second portions of the curve and the predetermined PULSE width is that point along the curve between its first and second portions. In other words, the predetermined PULSE width is the point where the F.sub.th versus .tau..sub.p relationship no longer applies, and, of course, it does not apply for PULSE widths shorter than the predetermined PULSE width.

The scaling of fluence breakdown threshold (F.sub.th) as a function of PULSE width (T) is expressed as F.sub.th proportional to the square root of (T.sup.1/2) is demonstrated in the PULSE width regime to the nanosecond range. The invention provides methods for operating in PULSE widths to the picosecond and femtosecond regime where we have found that the breakdown threshold (Fth) does not vary with the square root of PULSE width (T.sup.1/2).

PULSE width duration from nanosecond down to the femtosecond range is accomplished by generating a short optical PULSE having a predetermined duration from an optical oscillator. Next the short optical PULSE is stretched in time by a factor of between about 500 and 10,000 to produce a timed stretched optical PULSE to be amplified. Then, the time stretched optical PULSE is amplified in a solid state amplifying media. This includes combining the time stretched optical PULSE with an optical PULSE generated by a second LASER used to pump the solid state amplifying media. The amplified PULSE is then recompressed back to its original PULSE duration.

In one embodiment, a LASER oscillator generates a very short PULSE on the order of 10 to 100 femtoseconds at a relatively low energy, on the order of 0.001 to 10 nanojoules. Then, it is stretched to approximately 100 picoseconds to 1 nanosecond and 0.001 to 10 nanojoules. Then, it is amplified to typically on the order of 0.001 to 1,000 millijoules and 100 picoseconds to 1 nanosecond and then recompressed. In its final state it is 10 to 200 femtoseconds and 0.001 to 1,000 millijoules. Although the system for generating the PULSE may vary, it is preferred that the LASER medium be sapphire which includes a titanium impurity responsible for the lasing action.

In one aspect, the method of the invention provides a LASER BEAM which defines a spot that has a lateral gaussian profile characterized in that fluence at or near the center of the BEAM spot is greater than the threshold fluence whereby the LASER induced breakdown is ablation of an area within the spot. The maximum intensity is at the very center of the BEAM waist. The BEAM waist is the point in the BEAM where wave-front becomes a perfect plane; that is, its radius of curvature is infinite. This center is at radius R=0 in the x-y axis and along the Z axis, Z=0. This makes it possible to damage material in a very small volume Z=0, R=0. Thus it is possible to make features smaller than spot size in the x-y focal plane and smaller than the RAYLEIGH range (depth of FOCUS) in the Z axis. It is preferred that the PULSE width duration be in the femtosecond range although PULSE duration of higher value may be used so long as the value is less than the PULSE width defined by an abrupt or discernable change in slope of fluence breakdown threshold versus LASER BEAM PULSE width.

In another aspect, a diaphragm, disk, or mask is placed in the PATH of the BEAM to block at least a portion of the BEAM to cause the BEAM to assume a desired geometric configuration. In still further aspects, desired BEAM configurations are achieved by varying BEAM spot size or through Fourier Transform (FT) PULSE shaping to cause a special frequency distribution to provide a geometric shape.

It is preferred that the BEAM have an energy in the range of 10 nJ (nanojoules) to 1 millijoule and that the BEAM have a fluence in the range of 0.1 J/cm.sup.2 to 100 J/cm.sup.2 (joules per centimeter square). It is preferred that the wavelength be in a range of 200 nm (nanometers) to 1 .mu.m (micron).

Advantageously, the invention provides a new method for determining the optimum PULSE width duration regime for a specific material and a procedure for using such regime to produce a precisely configured cut or void in or on a material. For a given material the regime is reproducible by the method of the invention. Advantageously, very high intensity results from the method with a modest amount of energy and the spot size can be very small. Damage to adjoining area is minimized which is particularly important to human and animal tissue.

These and other object features and advantages of the invention will be become apparent from the following description of the preferred embodiments, claims, and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic representation of a LASER induced breakdown experimental system which includes a chirped PULSE amplification LASER system and means for detecting scattered and transmitted energy. If the sample is transparent, then transmitted energy can also be measured.

FIG. 2 is a plot of scattered energy versus incident fluence obtained for an opaque (gold) sample using the system in FIG. 1 operated at 150 femtoseconds (fs) PULSE duration.

FIG. 3 is a plot of calculated and experimental values of threshold fluence versus PULSE width for gold, with experimental values obtained for the gold sample using the system of FIG. 1 operated at 800 nm wavelength. The arrow shows the point on the plot where the F.sub.th proportional to T.sup.1/2 no longer applies, as this relationship only holds for PULSE widths down to a certain level as shown by the solid line.

FIG. 4 is a graphical representation of sub-spot size ablation/machining in gold based on arbitrary units and showing F.sub.th the threshold fluence needed to initiate material removal; Rs the spot size of the incident BEAM and Ra the radius of the ablated hole in the x-y plane.

FIG. 5 is a schematic illustration of a BEAM intensity profile showing that for LASER micro-machining with ultrafast PULSE according to the invention, only the peak of the BEAM intensity profile exceeds the threshold intensity for ablation/machining.

FIG. 6A and B are schematic illustrations of a BEAM showing the placement of a disk-shaped mask in the BEAM PATH.

FIG. 7 is a plot of scattered plasma emission and transmitted LASER PULSE as a function of incident LASER PULSE energy for a transparent glass sample, SiO.sub.2.

FIG. 8 is a plot of fluence threshold (F.sub.th) versus PULSE width (T) for the transparent glass sample of FIG. 7 showing that F.sub.th varying with T.sup.1/2 only holds for PULSE widths down to a certain level as shown by the solid line. Previous work of others is shown in the long PULSE width regime (Squares, Smith Optical Eng 17, 1978 and Triangles, Stokowski, NBS Spec Bul 541, 1978).

FIG. 9 is a plot of fluence threshold versus PULSE width for corneal tissue, again showing that the proportionality between F.sub.th and PULSE width follows the T.sup.1/2 relationship only for PULSE widths which are relatively long.

FIGS. 10 and 11 are plots of plasma emission versus LASER fluence showing that at 170 (FIG. 10) PULSE width the F.sub.th is very clearly defined compared to 7 nm (FIG. 11) PULSE width where it is very unclear.

FIG. 12 is a plot of impact ionization rate per unit distance determined by experiment and theoretical calculation.

FIGS. 13A and B are schematic illustrations of BEAM profile along the longitudinal Z axis and sharing precise control of damage--dimension along the Z axis.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1 there is shown an apparatus for performing tests to determine the LASER induced breakdown threshold as a function of LASER PULSE width in the nanosecond to femtosecond range using a chirped-PULSE

amplification (CPA) LASER system. The basic configuration of such a CPA system is described in U.S. Pat. No. 5,235,606 which is assigned to the assignee of the present invention and which has inventors in common with this present application. U.S. Pat. No. 5,235,606 is incorporated herein by reference in its entirety.

Chirped-PULSE amplification systems have been described by Jeffrey Squier and Gerard Mourou, two of the joint inventors in the present application, in a publication entitled LASER FOCUS World published by Pennwell in June of 1992. It is described that CPA systems can be roughly divided into four categories. The first includes the high energy low repetition systems such as ND glass LASERS with outputs of several joules but they may fire less than 1 shot per minute. A second category are LASERS that have an output of approximately 1 joule and repetition rates from 1 to 20 hertz. The third group consists of millijoule level LASERS that operate at rates ranging from 1 to 10 kilohertz. A fourth group of LASERS operates at 250 to 350 kilohertz and produces a 1 to 2 microjoules per PULSE. In U.S. Pat. No. 5,235,606 several solid state amplifying materials are identified and the invention of U.S. Pat. No. 5,235,606 is illustrated using the Alexandrite. The examples below use Ti:Sapphire and generally follow the basic process of U.S. Pat. No. 5,235,606 with some variations as described below.

The illustrative examples described below generally pertain to PULSE energies less than a microjoule and often in the nanojoule range with PULSE duration in the range of hundreds of picoseconds or less and the frequency on the order of 1 kilohertz. But these examples are merely illustrative and the invention is not limited thereby.

In a basic scheme for CPA, first a short PULSE is generated. Ideally the PULSE from the oscillator is sufficiently short so that further PULSE compression is not necessary. After the PULSE is produced it is stretched by a grating pair arranged to provide positive group velocity dispersion. The amount the PULSE is stretched depends on the amount of amplification. Below a millijoule, tens of picoseconds are usually sufficient. A first stage of amplification typically takes place in either a regenerative or a multipass amplifier. In one configuration this consists of an optical resonator that contains the gain media, a Pockels cell, and a thin film polarizer. After the regenerative amplification stage the PULSE can either be recompressed or further amplified. The compressor consists of a grating or grating pair arranged to provide negative group velocity dispersion. Gratings are used in the compressor to correspond to those in the stretching stage. More particulars of a typical system are described in U.S. Pat. No. 5,235,606, previously incorporated herein by reference.

An important aspect of the invention is the development of a characteristic

curve of fluence breakdown threshold F.sub.th as a function of LASER PULSE width specific to a material. Then identify on such curve, the point at which there is an abrupt, or distinct and rapid change or at least a discernable change in slope characteristic of the material. In general it is more desirable to operate past this point because of the more precise control of the LASER induced breakdown (LIB) or ablation threshold.

EXAMPLE 1

Opaque Material

FIG. 1 shows an experimental setup for determining threshold fluence by determining scattered energy versus incident fluence and by determining threshold fluence versus PULSE width. The system includes means for generating a PULSED LASER BEAM as described earlier, and means, typically a lens, for collecting emission from the target to a photomultiplier tube. Change of transmission through a transparent sample is measured with an energy meter.

FIG. 2 shows a plot of data obtained from an absorbing medium which is gold using 150 fs PULSE and FIG. 3 shows threshold fluence versus PULSE width. The arrow in FIG. 3 identifies the point at which the relationship between the threshold fluence and PULSE width varies dramatically.

In experimental conditions with wavelength of 800 nm and 200 fs PULSES on gold (FIG. 3), the absorption depth is 275 A with a diffusion length of 50 A. In the case of nanosecond PULSES the diffusion length, which is on the order of 10 .mu.m (micron) in diameter, is much longer than the absorption depth, resulting in thermal diffusion being the limiting factor in feature size resolution. Empirical evidence for the existence of these two regimes is as exhibited in FIG. 3. Here both experimental and theoretical ablation thresholds are plotted as a function of PULSE width. An arrow at approximately 7 picoseconds PULSE width (designated herein as T or .tau..sub.p) delineates the point (or region closely bounding that point) at which the thermal diffusion length (l.sub.th) is equal to the absorption depth (1/a). It is clear that for a smaller size spot a shorter (smaller) PULSE is necessary. For spot size on the order of 1000 .ANG. or less, PULSE width on the order of 100 femtoseconds or less will be needed. It is clear from the figure that this is the point at which the ablation threshold transitions from a slowly varying or nearly constant value as a function of PULSE width to one that is dramatically dependent on PULSE time. This result is surprising. It has been demonstrated that the electron thermalization time for LASER deposited energy in gold is on the order of, or less than, 500 fs and the electron-lattice interaction time is 1 ps. The consequences of this for ultrafast LASER PULSES is that the energy is

contained within the BEAM spot. In fact for energies at or near the threshold for ablation, the spatial profile of the LASER BEAM will determine the size and shape of the region being ablated (FIGS. 4 and 5).

Additional experiments were performed to measure the amount of recombination light produced as a function of the fluence impinging on a gold film. The technique involved is based upon the experimental setup previously described. A basic assumption is that the intensity of the light is proportional to the amount of material ablated. In FIG. 4, the material removed is plotted as a function of fluence. A well defined threshold fluence is observed at which material removal is initiated. By having only a small fraction of the gaussian BEAM where the fluence is greater than the threshold, the ablated region can be restricted to this small area. In FIG. 4, R.sub.a is the radial position on the BEAM where the fluence is at threshold. Ablation, then, occurs only within a radius R.sub.a. It is evident that by properly choosing the incident fluence, the ablated spot or hole can in principle be smaller than the spot size, R.sub.s. This concept is shown schematically in FIG. 5. Although the data for a 150 fs PULSE is shown in FIG. 4, this threshold behavior is exhibited in a wide range of PULSE widths. However, sub spot size ablation is not possible in the longer PULSE regimes, due to the dominance of thermal diffusion as will be described below.

Additional experiments on opaque materials used a 800 nm Ti:Sapphire oscillator whose PULSES were stretched by a grating pair, amplified in a regenerative amplifier operating at 1 kHz, and finally recompressed by another grating pair. PULSE widths from 7 ns to 100 fs were obtained. The BEAM was FOCUSed with a 10.times. objective, implying a theoretical spot size of 3.0 .mu.m in diameter. A SEM photo-micrograph of ablated holes obtained in a silver film on glass, using a PULSE width of 200 fs and a PULSE energy of 30 nJ (fluence of 0.4 J/cm.sup.2) produced two holes of diameter approximately 0.3 .mu.m in diameter. Similar results have been obtained in aluminum.

These results suggest that by, producing a smaller spot size which is a function of numerical aperture and wavelength, even smaller holes can be machined. We have demonstrated the ability to generate the fourth harmonic (200 nm) using a nonlinear crystal. Thus by using a stronger objective lens along with the 200 nm light, holes with diameters of 200 angstroms could in principle be formed.

These examples show that by using femtosecond PULSES the spatial resolution of the ablation/machining process can be considerably less than the wavelength of the LASER radiation used to produce it. The ablated holes have an area or diameter less than the area or diameter of the spot size.

In the special case of diffraction limited spot size, the ablated hole has a size (diameter) less than the fundamental wavelength size. We have produced LASER ablated holes with diameters less than the spot diameter and with diameters 10% or less of the LASER BEAM spot size. For ultrafast PULSES in metals the thermal diffusion length, l.sub.th =(Dt).sup.1/2 (where D is the thermal diffusivity and t the PULSE time), is significantly smaller than the absorption depth (1/a), where a is the absorption coefficient for the radiation.

Those skilled in the art will understand that the basic method of the invention may be utilized in alternative embodiments depending on the desired configurations of the induced breakdown. Examples include, but are not limited to using a mask in the BEAM PATH, varying spot size, adjusting FOCUS position by moving the lens, adjusting LASER cavity design, Fourier Transform (FT) shaping, using a LASER operating mode other than TEMoo, and adjusting the RAYLEIGH range, the depth of FOCUS or BEAM waist.

The use of a mask is illustrated in FIG. 6A and B. The basic method consists of placing a mask in the BEAM PATH or on the target itself. If it is desired to block a portion of the BEAM, the mask should be made of an opaque material and be suspended in the BEAM PATH (FIG. 6A) alternatively, the mask may be placed on the target and be absorptive so as to contour the target to the shape of the mask (FIG. 6B).

The varying spot size is accomplished by varying the laster f/#, i.e., varying the focal length of the lens or input BEAM size to the lens as by adjustable diaphragm.

Operation in other than the TEMoo mode means that higher order transverse modes could be used. This affects the BEAM and material as follows: the BEAM need not be circular or gaussian in intensity. The material will be ablated corresponding to the BEAM shape.

The RAYLEIGH range (Z axis) may be adjusted by varying the BEAM diameter, where the focal plane is in the x-y axis.

EXAMPLE 2

Transparent Material

A series of tests were performed on an SiO.sub.2 (glass) sample to determine the LASER induced breakdown (LIB) threshold as a function of LASER PULSE width between 150 fs-7 ns, using a CPA LASER system. The short PULSE LASER used was a 10 Hz Ti:Sapphire oscillator amplifier system based on the CPA technique. The LASER PULSE was FOCUSed by an f=25 cm lens inside

the SiO_2 sample. The RAYLEIGH length of the FOCUSED BEAM is .about.2 mm. The FOCUSED spot size was measured in-situ by a microscope objective lens. The measured spot size FWHM (full width at half max) was 26 .mu.m in diameter in a gaussian mode. The fused silica samples were made from Corning 7940, with a thickness of 0.15 mm. They were optically polished on both sides with a scratch/dig of 20-10. Each sample was cleaned by methanol before the experiment. Thin samples were used in order to avoid the complications of self-FOCUSING of the LASER PULSES in the bulk. The SiO_2 sample was mounted on a computer controlled motorized X-Y translation stage. Each location on the sample was illuminated by the LASER only once.

Two diagnostics were used to determine the breakdown threshold F_{th}. First, the plasma emission from the focal region was collected by a lens to a photomultiplier tube with appropriate filters. Second, the change of transmission through the sample was measured with an energy meter. (See FIG. 1) Visual inspection was performed to confirm the breakdown at a nanosecond PULSE duration. FIG. 7 shows typical plasma emission and transmitted light signal versus incident LASER energy plots, at a LASER PULSE width of τ_p =300 fs. It is worth noting that the transmission changed slowly at around F_{th}. This can be explained by the temporal and spatial behavior of the breakdown with ultrashort PULSES. Due to the spatial variation of the intensity, the breakdown will reach threshold at the center of the FOCUS, and because of the short PULSE duration, the generated plasma will stay localized. The decrease in transmitted light is due to the reflection, scattering, and absorption by the plasma. By assuming a gaussian profile in both time and space for the LASER intensity, and further assuming that the avalanche takes the entire PULSE duration to reach threshold, one can show that the transmitted LASER energy U_t as a function of the input energy U is given by

$U_t = kU, \; U \leq U_{th}$

$U_t = kU_{th} [1+\ln(U/U_{th})], \; U>U_{th}$

where k is the linear transmission coefficient. The solid curve in FIG. 7 is plotted using Eq. (1), with U_{th} as a fitting parameter. In contrast, breakdown caused by nanosecond LASER PULSES cuts off the transmitted BEAM near the peak of the PULSES, indicating a different temporal and spatial behavior.

FIG. 8 shows the fluence breakdown threshold F_{th} as a function of LASER PULSE width. From 7 ns to about 10 ps, the breakdown threshold follows the scaling in the relatively long PULSE width regime (triangles and squares) are also shown as a comparison--it can be seen that the

present data is consistent with earlier work only in the higher PULSE width portion of the curve. When the PULSE width becomes shorter than a few picoseconds, the threshold starts to increase. As noted earlier with respect to opaque material (metal), this increased precision at shorter PULSE widths is surprising. A large increase in damage threshold accuracy is observed, consistent with the multiphoton avalanche breakdown theory. (See FIGS. 8 and 9.) It is possible to make features smaller than spot size in the x-y focal plane and smaller than the RAYLEIGH range (depth of FOCUS) in the longitudinal DIRECTION or Z axis. These elements are essential to making features smaller than spot size or RAYLEIGH range.

EXAMPLE 3

Tissue

A series of experiments was performed to determine the breakdown threshold of cornea as a function of LASER PULSE width between 150 fs-7 ns, using a CPA LASER system. As noted earlier, in this CPA LASER system, LASER PULSE width can be varied while all other experimental parameters (spot size, wavelength, energy, etc.) remain unchanged. The LASER was FOCUSed to a spot size (FWHM) of 26 .mu.m in diameter. The plasma emission was recorded as a function of PULSE energy in order to determine the tissue damage threshold. Histologic damage was also assessed.

Breakdown thresholds calculated from plasma emission data revealed deviations from the scaling law, F.sub.th .alpha. T.sup.1/2, as in the case of metals and glass. As shown in FIG. 9, the scaling law of the fluence threshold is true to about 10 ps, and fail when the PULSE shortens to less than a few picoseconds. As shown in FIGS. 10 and 11, the ablation or LIB threshold varies dramatically at high (long) PULSE width. It is very precise at short PULSE width. These results were obtained at 770 nm wavelengths. The standard deviation of breakdown threshold measurements decreased markedly with shorter PULSES. Analysis also revealed less adjacent histological damage with PULSES less than 10 ps.

The breakdown threshold for ultrashort PULSES (<10 ps) is less than longer PULSES and has smaller standard deviations. Reduced adjacent histological damage to tissue results from the ultrashort LASER PULSES.

In summary, it has been demonstrated that sub-wavelength holes can be machined into metal SURFACES using femtosecond LASER PULSES. The effect is physically understood in terms of the thermal diffusion length, over the time period of the PULSE deposition, being less than the absorption depth of the incident radiation. The interpretation is further based on the hole diameter being determined by the lateral gaussian distribution of the PULSE

in relation to the threshold for vaporization and ablation.

LASER induced optical breakdown dielectrics consists of three general steps: free electron generation and multiplication, plasma heating and material deformation or breakdown. Avalanche ionization and multiphoton ionization are the two processes responsible for the breakdown. The LASER induced breakdown threshold in dielectric material depends on the PULSE width of the LASER PULSES. An empirical scaling law of the fluence breakdown threshold as a function of the PULSE width is given by F.sub.th .alpha. .sqroot..tau..sub.p, or alternatively, the intensity breakdown threshold, I.sub.th =F.sub.th /.tau..sub.p. Although this scaling law applies in the PULSE width regime from nanosecond to tens of picoseconds, the invention takes advantage of the heretofore unknown regime where breakdown threshold does not follow the scaling law when suitably short LASER PULSES are used, such as shorter than 7 picoseconds for gold and 10 picoseconds for SiO.sub.2.

While not wishing to be held to any particular theory, it is thought that the ionization process of a solid dielectric illuminated by an intense LASER PULSE can be described by the general equation

dne(t)/dt=.eta.(E)ne(t)+(dne(t)/dt).sub.PI -(dn.sub.e (t)/dt).sub.loss

where n.sub.e (t) is the free electron (plasma) density, .eta.(E) is the avalanche coefficient, and E is the electric field strength. The second term on the right hand side is the photoionization contribution, and the third term is the loss due to electron diffusion, recombination, etc. When the PULSE width is in the picosecond regime, the loss of the electron is negligible during the duration of the short PULSE.

Photoionization contribution can be estimated by the tunneling rate. For short PULSES, E.about.10.sup.8 V/cm, the tunneling rate is estimated to be w.about.4.times.10.sup.9 sec.sup.-1, which is small compared to that of avalanche, which is derived below. However, photoionization can provide the initial electrons needed for the avalanche processes at short PULSE widths. For example, the data shows at 1 ps, the rms field threshold is about 5.times.10.sup.7 V/cm. The field will reach a value of 3.5.times.10.sup.7 V/cm (rms) at 0.5 ps before the peak of the PULSE, and w.about.100 sec.sup.-1. During a .DELTA.t.about.100 fs period the electron density can reach n.sub.e .about.n.sub.t [1-exp(-w.DELTA.t)].about.10.sup.11 cm.sup.-3, where n.sub.t .about.10.sup.22 is the total initial valence band electron density.

Neglecting the last two terms there is the case of an electron avalanche process, with impact ionization by primary electrons driven by the LASER

field. The electron density is then given by n.sub.e (t)=n.sub.o .times.exp(n(E)t), where n.sub.o is the initial free electron density. These initial electrons may be generated through thermal ionization of shallow traps or photoionization. When assisted by photoionization at short PULSE regime, the breakdown is more statistical. According to the condition that breakdown occurs when the electron density exceeds n.sub.th .congruent.10.sup.18 cm.sup.-3 and an initial density of n.sub.o .congruent.10.sup.10 cm.sup.-3, the breakdown condition is then given by .eta..tau..sub.p .congruent.18. For the experiment, it is more appropriate to use n.sub.th .congruent.1.6.times.10.sup.21 cm.sup.-3, the plasma critical density, hence the threshold is reached when .eta..tau..sub.p .congruent.30. There is some arbitrariness in the definition of plasma density relating to the breakdown threshold. However, the particular choice of plasma density does not change the dependence of threshold as function of PULSE duration (the scaling law).

In the experiment, the applied electric field is on the order of a few tens of MV/cm and higher. Under such a high field, the electrons have an average energy of .about.5 eV, and the electron collision time is less than 0.4 fs for electrons with energy U.gtoreq.5-6 eV. Electrons will make more than one collision during one period of the electric oscillation. Hence the electric field is essentially a dc field to those high energy electrons. The breakdown field at optical frequencies has been shown to correspond to dc breakdown field by the relationship E.sup.rm.kappa..sub.th (w)=E.sup.dc.sub.th (1+w.sup.2 .tau..sup.2).sup.1/2, where w is the optical frequency and .tau. is the collision time.

In dc breakdown, the ionization rate per unit length, .alpha., is used to describe the avalanche process, with .eta.=.alpha.(E)v.sub.drift, where v.sub.drift is the drift velocity of electrons. When the electric field is as high as a few MV/cm, the drift velocity of free electrons is saturated and independent of the LASER electric field, v.sub.drift .congruent.2.times.10.sup.7 cm/s.

The ionization rate per unit length of an electron is just eE/U.sub.i times the probability, P(E), that the electron has an energy .gtoreq.U.sub.i, or .alpha.(E)=(eE/U.sub.i)P(E). Denoting E.sub.kT,E p, and E.sub.i as threshold fields for electrons to overcome the decelerating effects of thermal, phonon, and ionization scattering, respectively. Then the electric field is negligible, E<E.sub.kT, so the distribution is essentially thermal, P(E) is simply exp(-U.sub.i /kT). It has been suggested: P(E).about.exp(-const/E) for E.sub.kT <E<E.sub.p ; P(E).about.exp(-const/E.sup.2) at higher fields (E>E.sub.p). Combining the three cases the expression that satisfies both low and high field limits:

.alpha.(E)=(eE/U.sub.i)exp(-Ei/(E(1+E/E.sub.p)+E.sub.KT).

This leads to F.sub.th .alpha. E.sup.2 .tau..sub.p .about.1/.tau..sub.p, i.e., the fluence threshold will increase for ultrashort LASER PULSES when E>.sqroot.E.sub.p E.sub.i is satisfied.

FIG. 12 is a plot of .alpha. as a function of the electric field, E. From experimental data, calculated according to .eta..tau..sub.p =30 and .eta.=av.sub.drift. The solid curve is calculated from the above equation, using E.sub.i =30 MV/cm, E.sub.p =3.2 MV/cm, and E.sub.kT =0.01 MV/cm. These parameters are calculated from U=eEl, where U is the appropriate thermal, phonon, and ionization energy, and l is the correspondent energy relation length (l.sub.kT =l.sub.p .about.5 .ANG., the atomic spacing, and l.sub.i .congruent.30 .ANG.). It shows the same saturation as the experimental data. The dashed line is corrected by a factor of 1.7, which results in an excellent fit with the experimental data. This factor of 1.7 is of relatively minor importance, as it can be due to a systematic correction, or because breakdown occurred on the SURFACE first, which could have a lower threshold. The uncertainty of the saturation value of v.sub.drift also can be a factor. The most important aspect is that the shape (slope) of the curve given by the equation provides excellent agreement with the experimental data. Thus, the mechanism of LASER induced breakdown in fused silica (Example 2), using PULSES as short as 150 fs and wavelength at 780 nm, is likely still dominated by the avalanche process.

Opaque and transparent materials have common characteristics in the curves of FIGS. 3, 8, and 9 each begins with F.sub.th versus T.sup.1/2 behavior but then distinct change from that behavior is evident. From the point of deviation, each curve is not necessarily the same since the materials differ. The physical characteristics of each material differ requiring a material specific analysis. In the case of SiO.sub.2 (FIG. 8) the energy deposition mechanism is by dielectric breakdown. The optical radiation is releasing electrons by multiphoton ionization (M PI) that are tightly bound and then accelerating them to higher energies by high field of the LASER. It is thought that only a small amount of relatively high energy electrons exist prior to the LASER action. The electrons in turn collide with other bound electrons and release them in the avalanching process. In the case of metal, free electrons are available and instantly absorbing and redistributing energy. For any material, as the PULSES get shorter LASER induced breakdown (LIB) or ablation occurs only in the area where the LASER intensity exceeds LIB or ablation threshold. There is essentially insufficient time for the surrounding area to react thermally. As PULSES get shorter, vapor from the ablated material comes off after the deposition of the PULSE, rather than during deposition, because the PULSE duration is so short. In summary, by the method of the invention, LASER induced

breakdown of a material causes thermal-physical changes through ionization, free electron multiplication, dielectric breakdown, plasma formation, other thermal-physical changes in state, such as melting and vaporization, leading to an irreversible change in the material. It was also observed that the LASER intensity also varies along the propagation axis (FIG. 13). The BEAM intensity as a function of R and Z expressed as:

I((Z, R)=I.sub.o /(1+Z/Z.sub.R).sup.2 .multidot.exp(-2R.sup.2 /W.sup.2.sub.z)

where Z.sub.R is the RAYLEIGH range and is equal to ##EQU1## W.sub.o is the BEAM size at the waist (Z=0).

We can see that the highest value of the field is at Z=R=0 at the center of the waist. If the threshold is precisely defined it is possible to damage the material precisely at the waist and have a damaged volume representing only a fraction of the waist in the R DIRECTion or in the Z DIRECTion. It is very important to control precisely the damage threshold or the LASER intensity fluctuation.

For example, if the damage threshold or the LASER fluctuations known within 10% that means that on the axis (R=0)

I(0,Z)/I.sub.o =1/(1=(Z/Z.sub.R).sup.2 =0.9

damaged volume can be produced at a distance Z.sub.R /3 where Z.sub.R again is the RAYLEIGH range. For a BEAM waist of W.sub.o =.lambda. then ##EQU2## and the d distance between hole can ##EQU3## as shown in FIG. 13.

The maximum intensity is exactly at the center of the BEAM waist (Z=0, R=0). For a sharp threshold it is possible to damage transparent, dielectric material in a small volume centered around the origin point (Z=0, R=0). The damage would be much smaller than the BEAM waist in the R DIRECTion. Small cavities, holes, or damage can have dimensions smaller than the RAYLEIGH range (Z.sub.R) in the volume of the transparent, dielectric material. In another variation, the lens can be moved to increase the size of the hole or cavity in the Z dimension. In this case, the focal point is essentially moved along the Z axis to increase the longitudinal dimension of the hole or cavity. These features are important to the applications described above and to related applications such as micro machining, integrated circuit manufacture, and encoding data in data storage media.

Advantageously, the invention identifies the regime where breakdown threshold fluence does not follow the scaling law and makes use of such

regime to provide greater precision of LASER induced breakdown, and to induce breakdown in a preselected pattern in a material or on a material. The invention makes it possible to operate the LASER where the breakdown or ablation threshold becomes essentially accurate. The accuracy can be clearly seen by the I-bars along the curves of FIGS. 8 and 9. The I-bars consistently show lesser deviation and correspondingly greater accuracy in the regime AT OR BELOW the predetermined PULSE width.

While this invention has been described in terms of certain embodiment thereof, it is not intended that it be limited to the above description, but rather only to the extent set forth in the following claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined in the appended claims.

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